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We demonstrate, for the first time, to our knowledge, a diode-pumped passively mode-locked Nd:YVO_4 laser, operating on the $^4F_{3/2}$–$^4I_{9/2}$ transition of the neodymium ion at 914 nm. We obtained 8.8 ps pulses at approximately 914 nm at a repetition rate of 94 MHz, and an averaged output power of 87 mW by using a semiconductor saturable absorber mirror. © 2006 Optical Society of America

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During the past few years, the $^4F_{3/2}$–$^4I_{9/2}$ transition near 900–950 nm of the neodymium ion has attracted a lot of attention: it enables one to generate blue and visible wavelengths by means of frequency doubling. In fact, diode-pumped systems based on Nd-doped materials, such as Nd:YAG or Nd:YVO_4, currently used on $^4F_{3/2}$–$^4I_{11/2}$ transitions in the 1 μm range, are well known for their efficiency and their simplicity. The idea of transposing such systems to the 900 nm region is attractive. Indeed, the blue diode-pumped solid-state laser (blue DPSSL) has, over the past few years, become one of the most active fields of research in laser physics. Blue radiation finds many applications, especially in biology and medicine, since many fluorophores have an absorption band in this wavelength range. For example, it would be attractive to apply a simple and compact picosecond source emitting in the blue near 450 nm to fluorescence lifetime microscopy.

The use of a commercially available fiber-coupled pump diode to develop a simple and user-friendly laser seems interesting. At first sight, Nd:YVO_4 with its transition at 914 nm seems an interesting candidate since one can use standard high-power laser diodes emitting at 808 nm.[1] But operating Nd:YVO_4 at 914 nm is quite difficult and requires fine adjustments. First, at this wavelength, the neodymium ion behaves like a quasi-three-level system. Indeed, the $^4I_{9/2}$ level is only 433 cm^{-1} above the ground state.[2] Consequently this level has a high thermal population of 5% at room temperature, which limits the population inversion. This leads to a strong reabsorption when the inversion density is not sufficient. In order to obtain efficient laser operation, bright pumping is required to increase the population inversion. Besides, a low doped and not too long crystal is preferred to reach approximately 70% of pump absorption. Second, the ratio between the emission cross sections at 914 nm and at 1064 nm is 0.04.[3] It shows that we must introduce high cavity losses at 1064 nm in order to favor the emission at 914 nm. Moreover, the emission cross section at 914 nm is weak and leads to a high lasing threshold that requires strong pump intensity. All these points explain the lack of pulsed diode-pumped lasers emitting at 914 nm. Indeed, most previous works have focused on the $^4F_{3/2}$–$^4I_{9/2}$ transition at 946 nm of the Nd:YAG, far more accessible because the thermal properties of this crystal are superior to those of Nd:YVO_4 and the ratio of the emission cross sections is twice as high (0.09) in this case.

A passively mode-locked 914 nm laser was demonstrated recently by Schlatter *et al.*,[4] but a Ti:sapphire pump laser with a limited diffraction beam was used. This excellent work made it possible to understand the difficulty of mode locking on the $^4F_{3/2}$–$^4I_{9/2}$ transition at 914 nm of the Nd:YVO_4 and to appreciate the complexity of the next step, which consisted of direct diode pumping.[4,5] This Letter is dedicated to the following step and describes the realization of what is believed to be the first diode-pumped passively mode-locked laser at 914 nm.

As a preliminary experiment, we tested the Nd: YVO_4 laser at 914 nm (Fig. 1) in cw operation under diode pumping. The gain medium was a 4 mm thick 0.2% doped Nd: YVO_4 crystal with antireflec-

Fig. 1. (Color online) Experimental setup for (a) cw operation and (b) the mode-locked regime. (a) M1, HT at 1064 nm, $R=97\%$ at 914 nm; M2, HT at 1064 nm, HR at 914 nm, radius of curvature (RoC)=200 mm; M3: HT at 808 and 1064 nm, HR at 914 nm; L1: $f=50$ mm; L2: $f=80$ mm. Distances: M1–M2=600 mm, M2–crystal=105 mm, crystal–M3=5 mm. (b) M4, HT at 1064 nm, HR at 914 nm, RoC=200 mm; M5, HT at 1064 nm, HR at 914 nm, RoC =100 mm. Distances: M1–M2=600 mm, M2–crystal =105 mm, crystal–M3=20 mm, M3–M4=85 mm, M4–M5=700 mm, and M5–SESAM=50 mm.

tion coating. It was placed into a copper mount that was water cooled at 20°C. The pump source was a fiber-coupled diode emitting at 808 nm with a core diameter of 100 μm, a numerical aperture of 0.22, and a maximal power of 10 W. The fiber output was relay-imaged into the crystal by two doublets (L1 and L2 in Fig. 1) to obtain a pump spot diameter of 160 μm, which appeared experimentally to be an optimum, taking into account the brightness of the diode. Under these conditions, the pump power absorbed by the crystal was 63%. All mirrors had high-reflection (HR) coatings at 914 nm and supported a high-transmission (HT) coating at 1064 nm to prevent the laser effect on this strong transition (mirrors from Laseroptik: HT 1064 nm, $T>74\%$; HR 914 nm, $R>99.9\%$). The output coupler had a transmission of 3% at 914 nm.

The laser was a classical three-mirror cavity [Fig. 1(a)]. At maximum pump power corresponding to an incident power of 8.3 W on the crystal, we obtained 1.12 W of output power, similar to the best performance previously reported.[1]

The second cavity was built with five mirrors and a semiconductor saturable absorber mirror (SESAM) [Fig. 1(b)]. The first part of the cavity was kept the same as previously reported. We simply tilted mirrors M3 slightly and we added mirror M4, mirror M5, and the SESAM. First, we replaced the SESAM with a plane mirror so that our new cavity would perform in cw with the pump conditions of mode locking. We obtained 0.55 W at 914.0 nm (6.6 W of incident pump power on the crystal) with an optimized pump wavelength of 809 nm. This decrease of the output power illustrated the influence of the gain. In fact, since the laser operated with low gain, a small extra amount of loss implied a significant decrease in average power.

Then we put the SESAM in the cavity. To operate in passive mode locking, we chose commercially available SESAMs from Batop GmbH, Germany. Unfortunately, these SESAMs were designed for mode locking at 940 nm. Nevertheless, their high-reflection band was 910–990 nm, and so at 914 nm we used that band in the edge. We tested two SESAMs, with saturable absorption of 4% and 2% at 940 nm, corresponding to 4% and 3% at 914 nm.[6] The weak cross section at 914 nm necessitates relatively low losses in order to obtain stable mode locking without Q-switch instabilities.[7] We kept the output coupler with a transmission of 3%. We experimentally selected a 100 mm radius-of-curvature mirror for M5 to focus on the SESAM in order to reach a stable mode locking. This experimental choice corresponded to the optimal fluence for both SESAMs. The calculated corresponding spot radii were then 29 and 31 μm in the sagittal and tangential directions on the SESAM, respectively. We succeeded in operating the laser in a pure cw mode-locking regime with both SESAMs. We report here the results obtained with the 3% at 914 nm SESAM because the output power was twice that reached with the 4% SESAM with the same pulse duration and spectrum. Nevertheless, in the latter case, we observed a slightly larger domain of stability and a cw mode-locked condition that was a little bit easier to obtain. With the 3% at 914 nm SESAM, stable mode-locking operation was observed with an incident pump power of 7.2 W on the crystal. We then obtained an output power of 87 mW (which corresponds to an optical–optical efficiency of 1.3%). The laser was mode locked at a repetition rate of 94 MHz, which means a fluence of 3.4 mJ/cm^2 on the SESAM. We measured the duration of the pulses by using an autocorrelator (Fig. 2). After fitting the autocorrelation signal with a sech-squared shape, we obtained a FWHM pulse duration of 1.54×8.8 ps. The corresponding spectrum is centered at 913.8 nm with a width of 0.26 nm (Fig. 3). These values correspond to a time–bandwidth product of 0.82, which is 2.6 times the transform limit for sech^2 pulses. We also measured the spectrum in a large-scale domain in order to observe simultaneously the 1064 nm range (Fig. 3, inset), and the emission was clearly present only at 914 nm.

When obtained, the mode-locked regime was stable for hours, and no Q-switch modulations could be observed (Fig. 4). Nevertheless, the domain of stability versus the laser fluence on the SESAM was very short and complicated to obtain. In fact, mode-locking operation could only be observed for an output laser power between 85 and 87 mW (or a laser in-

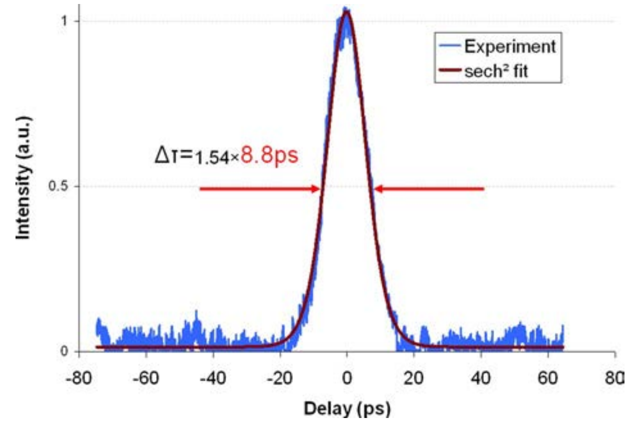

Fig. 2. (Color online) Autocorrelation trace of pulses obtained at 913.8 nm. Duration, 8.8 ps assuming a sech^2 shape.

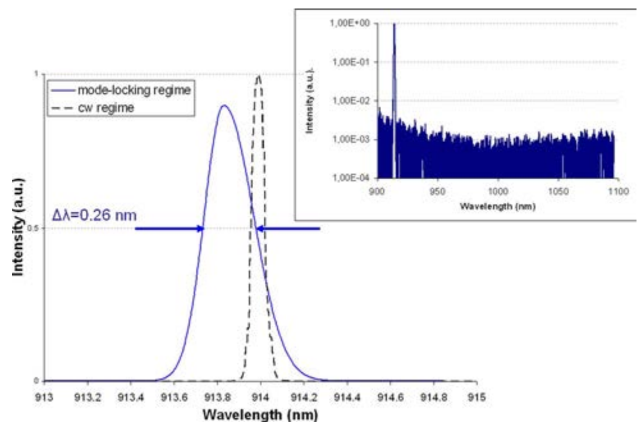

Fig. 3. (Color online) Optical spectrum of the 8.8 ps pulses at 913.8 nm (solid curve) and natural cw spectrum (dashed curve). The inset represents the 8.8 ps pulse spectrum with a large scale to show off the absence of the 1064 nm line.

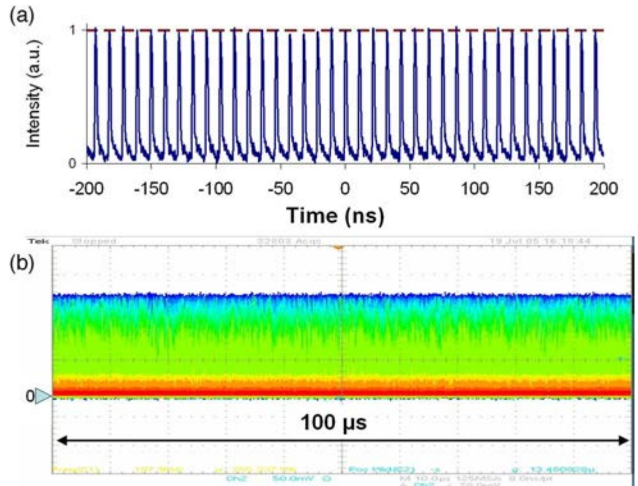

Fig. 4. (Color online) Pulse trains observed with two different time scales: (a) 400 ns, (b) 100 μs.

fluence on the SESAM between 1.07 and 1.09 mJ/cm^2). Under 85 mW and above 87 mW, we immediately observed Q-switch instabilities. This effect may be explained by the nature of the SESAM—it is not exactly designed for 914 nm—which leads to stable mode locking only for a very short range of laser fluence. In fact, we think the use of the SESAM at the very edge of its operating range is not optimal for high stability. Finally, the last deleterious consequence of this small stability domain was the difficulty of and the precision required for the alignment of the laser cavity, especially on the SESAM subcavity. Experimentally, this tricky alignment needed to be done for every switch on of the laser in order to reach the long-term stable mode-locked regime.

In conclusion, we have demonstrated what is to our knowledge the first diode-pumped passively mode-locked Nd:YVO_4 laser, operating on the $^4F_{3/2}$–$^4I_{9/2}$ transition of the Nd ion at 914 nm. This work represents the first step toward a new range of wavelengths for directly picosecond diode-pumped solid-state lasers based on Nd-doped materials. We obtained 8.8 ps pulses at a repetition rate of 94 MHz at 913.8 nm. The output power was 87 mW. Nevertheless, additional work remains to be done to make this system more user friendly, especially concerning the stability. Since up to now, no SESAM specially designed for 914 nm had been commercially available, we look forward to performing future work with better-adapted SESAMs, which would offer better laser stability, robustness, and efficiency.

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